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OPTICALLY-PROCESSED ROUTING CONTROL FOR FAST PACKET SWITCHES

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13. ABSTRACT (Maximum 200 words)

It is well known that optical fibers possess enormous transmission bandwidth capacity (on the order of 10-20 THz). However, due to the limitations of electronic circuit bandwidths at the transmit and receive nodes, in order to fully utilize this bandwidth, a shared medium protocol must be employed. Optical shared medium protocols involve multiplexing techniques, such as time-, wavelength-, or space division or sub-carrier multiplexing. In time-division multiplexing, high-speed routing and contention resolution are required. Such needs point to the development of optical gating devices to achieve this functionality. This work describes the requirements and implementation of new architectures and components for all-optical interconnects approaching these terahertz bandwidth capacities.

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Introduction

Although optical fibers provide the enormous transmission bandwidth required by emerging broadband network and high-performance computing applications, full access to this bandwidth is currently limited by electronic bottlenecks. To fully utilize the bandwidth of the optical fiber, high-speed multiplexing and demultiplexing are required, as well as high-speed routing control and contention resolution in packet-switched systems. Whereas electronic gates are currently able to achieve speeds of only a few GHz, optical gates can offer speeds in the THz regime, which is commensurate with the bandwidth of the fiber.

Several key issues must be addressed to achieve ultra-high processing speeds in optical communications and computing systems. Through close collaboration with Rome Laboratories during the past years, we have made substantial progress, both experimentally and theoretically, in our investigations of ultrafast optical processing. Our major achievements are:

• the first demonstration of a semiconductor mode-locked laser which produces ultrafast optical pulses and which can be rapidly tuned over a broad spectral range; 10 ps pulses are produced, and tuned over a 10 nm spectral range in less than a ns; this is a compact, robust, easily packaged device which has important practical applications to both wavelength- and time-multiplexed fiber-optic networks; the details are reported in:

P. P. Ianonne, G. Raybon, U. Koren and P. R. Prucnal, "Robust electrically tunable 1.5 micron mode-locked fiber-external-cavity laser," Appl. Physics Lett. **61**, 1496 (1992).

• the demonstration of a world-record-speed optical 'AND' gate, cascaded with an optical 'XOR' gate; using 285 femtosecond optical soliton pulses, a 22:1 contrast ratio was observed using 46 pJ switching energy; these ultrafast soliton gates have application to switching and time-demultiplexing in ultrafast long-haul soliton transmission systems, where 10 Gbps data streams are transmitted over thousands of kilometers without optical-to-electrical conversion; the details are reported in:

M. W. Chbat, B. Hong, M. N. Islam, C. E. Soccolich and P. R. Prucnal, "Ultrafast soliton-trapping AND gate," IEEE J. Lightwave Tech. **10**, (1994)

• the development of ultrafast self-routing for photonic switching systems based upon the technology described above; these ultrafast self-routing schemes were applied to 2D switching arrays using a novel lattice interconnection architecture; this work is reported in:

P. R. Prucnal, "Optically-process self-routing, synchronization and contention resolution fro 1D and 2D photonic switching architectures," IEEE J. Quantum Electronics, **29**, 600-612 (1993), (invited paper).

In the past year, in the "**Optically-Processed Routing Control for Fast Packet Switches**", we have investigated following issues:

a) network performance analysis and deflection routing
b) implementation and experimental demonstration of new architectures for photonic ATM switching nodes
c) implementation and experimental demonstration of newly developed ultra-fast all-optical demultiplexer ("TOAD") for:
- ultra-high speed all-optical demultiplexing in the Optical Time Division Multiplexed (OTDM) systems
- all-optical address recognition and routing of photonic packets
- self-clocking optical network

Obtained results:

a)

A new single-receiver/single-transmitter/single-buffer node structure for fast packet-switching two-connected transparent optical networks, using three 2x2 crossbar switches was analyzed.

We have proposed a simple node structure for single-buffer deflection routing in two-connected transparent optical networks. Except for the fiber delay loop, the structure can be integrated to reduce the overall power loss to below 10 dB. The per-packet processing time was 92 ns using a commercially available CMOS PLA. Given the simplicity of the routing and access algorithm, much shorter processing times can be achieved by using a more sophisticated electronic controller. Although quite simple, the routing algorithm yields more than 70% of the maximum achievable throughput in uniform traffic. Less benign traffic patterns, however, may degrade this throughput figure.

b)

A new transparent optical node for an ATM packet switch operating at 1.24416 Gbps data rates and 1.2 μm wavelength was developed. The node takes advantage of the high-speed performance of optoelectronic components to alleviate potential bottlenecks resulting from optical to electrical conversions experienced in non-transparent packet switching architectures. The node is intended for use in two-connected, slotted networks, is self clocking and has drop/add multiplexing, buffering and routing capabilities.

c)

An analysis of the optical loop mirror known as the TOAD was carried out for the case when the nonlinear optical element was placed asymmetrically in the loop. It is shown that this configuration permits the optical input to be sampled at the output by means of an optical control pulse. Two special loop configurations are analyzed, corresponding to small and large asymmetries in the placement of the nonlinear element. The small-asymmetry loop permits low-power ultra-fast all-optical sampling and demultiplexing to be performed using a relatively low optical nonlinearity. For this type of switch the size of the loop is completely irrelevant to switching operation as long as the required degree of asymmetry is accommodated. This is therefore the first low-power, ultra fast all-optical switch that can be integrated on a single substrate.

<u>- ultra-high speed all-optical demultiplexing</u>

The relatively low transmission bandwidth of the electronic, the associated optoelectronic interfaces, optoelectronic demultiplexers present an obstacle to fully utilizing the large bandwidth of the optical fiber. This obstacle could be overcome if signals remained in optical form during demultiplexing, switching and signal processing. We have reported the first demonstration of all-optical demultiplexing of TDM data at 250 Gb/s. The demultiplexer, called a "TOAD", is compact and requires sub-picojoule switching energy. Cross-talk measurements of pseudorandom data in adjacent, 4 ps-width time slots, exhibit a BER of less than 10^{-9}, with strong jitter immunity.

<u>- all-optical address recognition and routing of photonic packets</u>

In high traffic, parallel processing networks an interconnection field of switching nodes is used to simultaneously transmit optical packets between users. Each switching node must perform several functions one of the most important of which is packet routing. In ultra-high speed networks individual address bits are spaced only picoseconds apart, and address recognition must be performed by using an ultra-fast demultiplexer to read each address bit. Once the address bits in a packet header are read the state of the routing switch can be set to properly route the packets. We have reported the first demonstration of all-optical address recognition and self-routing of photonic packets for a case where the packet bit period is only 4 ps, corresponding to a 0.25 Tb/s bandwidth optical network. An ultrafast all-optical device, known as a terahertz optical asymmetric demultiplexer (TOAD), was used to read the address information encoded in a packet header, which in turn was used to route the packet. The bit-error rate at the switch output was measured to be less than 10^{-9}.

- self-clocking architectures of optical networks

Proper synchronization is one of the key issues for the error-free performance of such Tb/s OTDM networks. One promising method for synchronization is to distribute the optical clock to all transmitters and receivers in the network on the same low dispersion optical fibers as the transmitted data, using polarization multiplexing. We have reported the first demonstration of all-optical time-demultiplexing at 250 Gb/s with self-clocking using polarization multiplexing of the clock and data. To achieve such high speed, an ultra-high speed device known as the Terahertz Optical Asymmetric Demultiplexer (TOAD) is used. We also demonstrate self-clocked address recognition and routing control of a photonic switch at 250 Gb/s. The bit-error rate at the switch output was measured to be less than 10^{-9}.

Optical time division DeMUX- systems requirements, device capabilities and results

High bandwidth demultiplexing is important in optical time division multiplexed (OTDM) communication systems because the demultiplexer (DMUX) is the element which limits the system's total throughput. While all other components must operate, at most, at an individual user's data rate, the DMUX must operate at the aggregate bandwidth of the multiplexed system.[1-3]

Recently developed soliton gates,[4] and nonlinear optical loop mirrors (NOLMs) using both linear and soliton pulses,[5-8] have been shown to switch several hundred femtosecond long pulses.

These devices use the small non resonant nonlinearity in a fiber, and therefore require long lengths of fiber, as well as other costly components. For example, soliton gates require hundreds of meters of special fiber as well as non commercial laser sources, and high energy (about 100 picojoule) control pulses. NOLMs can operate with much lower energy (about 1 picojoule) control pulses, but often require a kilometer or more of fiber. A complete NOLM also often includes expensive parts such as diode laser pumped Erbium doped fiber amplifiers (EDFAs), multiple laser wavelength systems, wavelength selective couplers, and long lengths of polarization maintaining fiber cross-axis spliced to compensate for control pulse -- signal pulse walk-off.

Our newly developed device the TOAD differs from either of these devices in that it uses large, resonant, nanosecond lifetime optical nonlinearities found in semiconductor materials and devices. Because of this: 1) it operates with less than 1 picojoule control pulses, yet is small enough to be integrated on a chip, 2) it is wavelength compatible with all of the low loss transmission windows of optical fibers and not, as in the case of many NOLMs, just at wavelengths compatible with EDFAs, and 3) control and signal pulses can be distinguished either by polarization, or by wavelengths tens of nanometers apart since control-signal walk-off is not an issue. A TOAD, is capable of demultiplexing Tbit/s pulse trains with less than one picojoule of switching energy, and can be integrated on a chip. TOAD is capable of operation at 250 Gbit/s using 600 fJ control pulses. This work has been performed in close cooperation with Drs. Ray Boncek and John Stacy for Rome Laboratories and the members of the Lightwave Communications Research Laboratory, Paul R. Prucnal, Ivan Glesk, and Jason P. Sokoloff, at Princeton University. These results have resulted in a patent disclosure, a joint post-deadline papers and several journal and conference publications. The device consists of a nonlinear element, such as a semiconductor, asymmetrically placed in a short fiber loop, and uses the large slow resonant optical nonlinearities which all other fast demultiplexers seek to avoid. The TOAD functions as a fast gate which uses one pulse to both open and close this gate, with the "ON" time determined by the off-center position of the nonlinear element within the loop. The only fundamental limit on this device is the decay time of the femtosecond transient nonlinearities which precedes the slower recovering component of an optical nonlinearity.

TOAD - ultrafast all-optical demultiplexer

In a conventional loop mirror, which consists of a 2x2 3dB coupler with the ports joined, light enters the loop through the coupler, splits and counterpropagates around the loop, and then interferes at the coupler so as to emerge from the port it entered. However, some light will emerge from the alternate port if the light propagating in the loop experiences an absorption or index difference relative to its counter propagating complement. In the case of an absorption difference there is incomplete modal cancellation at the alternate port. In the case of an index difference there is a change in the relative phase of the complementary components which leads to incomplete cancellation at the alternate port.

The TOAD consists of a loop mirror with an additional 2x2 coupler, and a NLE offset from the loop center C by a distance Dx. A pump or control pulse injected directly into the NLE, via the intraloop 2x2 coupler, opens two temporal "windows", each having the time dependence of eq.(2), and allowing the possibility for light entering the loop at the input port, to exit the loop at the output port, as shown in figure. Light traveling either towards *or* away from the loop center (point C) and entering the SOA just after the control pulse, interferes with its counter propagating complement and emerges at the output port. The temporal separation of these two windows is $2(\Delta x)/c$, where Δx is the off-center position (asymmetry) of the SOA, and c is the speed of light in fiber. The full window function of the TOAD, for a control pulse arriving at the NLE at time t_o, can now be written as

$$W(t) = W_o \cdot \mathrm{abs}\{U(t-t_o-t_l) \cdot \exp(-(t-t_o-t_l)/t_{rec}) - U(t-t_o-t_l-2dx/c) \cdot \exp(-(-t_o-t_l-2dx/c)/t_{rec})\} \quad (4)$$

where abs{ } is the absolute value function, the latency time, t_l, is the shorter of the two propagation times between the loop mirror coupler and the NLE, and W_o is the maximum amplitude of the window. The intensity of light which will emerge from the TOAD, either cw or pulsed, is

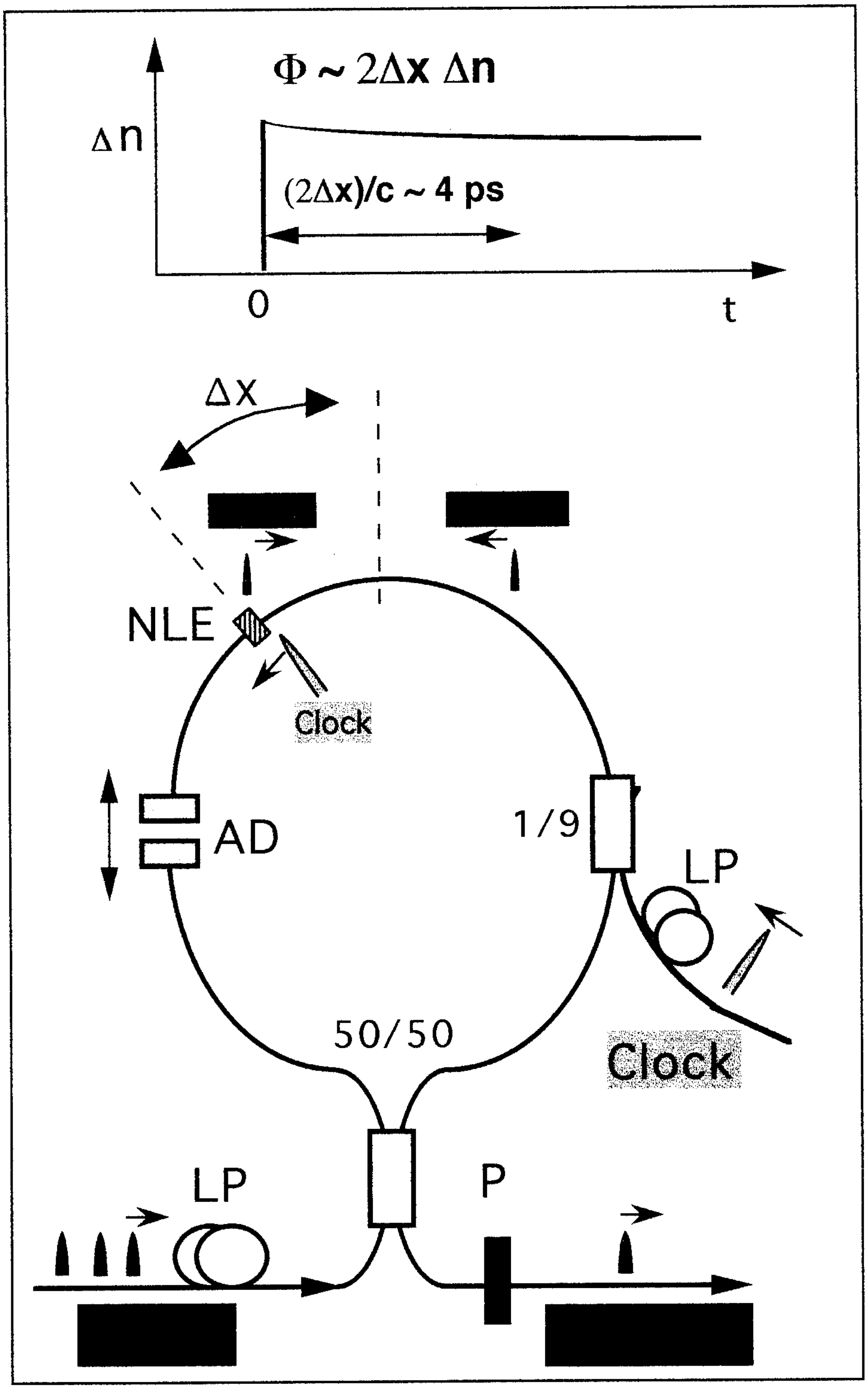
$$I_{out}(t) = I_{in}(t-t_l) \cdot W(t-t_l). \quad (5)$$

For the application of the TOAD as a TDM DMUX, we design the system such that $t_s << t_{rec}$, position the SOA such that $dx = v_s/2$, and set the control pulse within the time frame so that $t_o = j \cdot t_s$, where j is a channel number. In this case eq. (4) reduces to the difference between two step functions

$$W(t) = \begin{cases} 1 & j \cdot t_s + t_l < t < (j+1) \cdot t_s + t_l \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

and, once again, the signal at the output is described by eq.(5). Eqs. (5) and (6) say that if, and only if, a signal pulse arrives at the NLE during the t_s seconds following the control pulse's

Operation of the TOAD



arrival, then it will be at least partially switched out of the TOAD. The one control pulse turns the TOAD both on *and* off. Note also that by simply adjusting the NLE asymmetry, Δx, the slot time width can be adjusted as desired.

To improve performance of the TOAD several technical changes were made in its design and device was packaged:

a) A new generation of an adjustable delay, AD, was designed and manufactured. To improve throughput and also decrease back reflection from AD a special types of the grin-lenses were used to replace two aspherical lenses used by the old unite. These grin-lenses are on both sides angled and anti-reflection coated. This new AD has back reflection less than -65 dB which is 30 dB lower value.

b) Position of an adjustable delay, was changed inside of the loop to eliminate clock back reflections of this unite.

c) FC/PC connectors attaching SOA to the loop were replaced with higher performance FC/APCs FC/APC connectors have about two orders of magnitude lower back reflection per connection

d) A fusion splicing technique was used to eliminate mechanical connections previously done by "low performance" FC/PC connectors (about 0.3 dB loss and about -45 dB back reflection per each connection). By doing that the back reflections were practically eliminated and 0.02 dB loss per connection was achieved.

Conclusion

<u>Summary of obtained results:</u>

- Demonstration of the TOAD device using a semiconductor optical amplifier at wavelength l=1.3 μm; measurements of the response time, switching energy, contrast ratio, and inter-pulse crosstalk; find the bit-error rate as a function of switching energy.

J. P. Sokoloff, I. Glesk, P. R. Prucnal, and R. K. Boncek, "Performance of a Terahertz Optical Asymmetric Demultiplexer in 50 Gbit/s Optical Time Division Multiplexed System," SPIE Conference on Multigigabit Fiber Communication Systems, vol. 2024, p. 145, San Diego, CA, July 13-14, 1993

M. G. Kane, I. Glesk, J. P. Sokoloff, and P. R. Prucnal, "Asymmetric Optical Loop Mirror: Analysis of an All-Optical Switch," Applied Optics **33**, 6833 (1994)

J. P. Sokoloff, I. Glesk, P. R. Prucnal, and R. K. Boncek, "Performance of 50 Gbit/s Optical Time Domain Multiplexed System Using a Terahertz Optical Asymmetric Demultiplexer," IEEE Photonics Technology Letters **6**, 98 (1994)

J. P. Sokoloff, P. R. Prucnal, I. Glesk, and M. Kane, "A Terahertz Optical Asymmetric Demultiplexer (TOAD)," IEEE Photonics Technology Letters **5**, 787 (1993)

J. P. Sokoloff, P. R. Prucnal, I. Glesk, and M. Kane, "A Terahertz Optical Asymmetric Demultiplexer (TOAD)," OSA Conference on Switching in Photonics, Post deadline paper #4 (PD-4), Palm Springs, CA, March 6-9, 1993

- Demonstration of ultrafast all-optical 250 Gb/s demultiplexing capability of the TOAD.

I. Glesk, J. P. Sokoloff, and P. R. Prucnal, "Demonstration of All-Optical Demultiplexing of TDM Data at 250 Gb/s," Electronics Letters **30**, 339 (1994)

- Demonstration of self-clocking capability of the TOAD.

I. Glesk, J. P. Sokoloff, and P. R. Prucnal, "All-Optical Self Clocked Demultiplexing of TDM Data at 250 Gb/s," Proc. of 28th CISS, vol. 1, p. 491, Princeton, NJ, March 16-18, 1994

P. R. Prucnal, I. Glesk, and J. P. Sokoloff, "Demonstration of All-Optical Self Clocked Demultiplexing of TDM Data at 250 Gb/s," Invited paper, IEEE Computer Society First

International Workshop on Massively Parallel Processing Using Interconnections, p. 106, Cancún, Mexico, April 26-29, 1994

- Investigation of design and integration issues including the integration of subsystems.

W. C. Kwong, P. R. Prucnal, J. P. Sokoloff, and I. Glesk, "Ultrafast All-Optical Photonic Packet Switching," Invited paper, SPIE Conference on Multigigabit Fiber Communication Systems, vol. 2024, p. 150, San Diego, CA, July 13-14, 1993

- The development of ultrafast self-routing for photonic switching systems based upon our developed technology; these ultrafast self-routing schemes were applied to 2D switching arrays using a novel lattice interconnection architecture; this work is reported in:

P.R. Prucnal, (1993). "Optically-process self-routing, synchronization and contention resolution fro 1D and 2D photonic switching architectures," IEEE J. Quantum Electronics, vol. 29, no. 2, 600-612 (invited paper).

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A. Bononi, R.K. Boncek, P.R. Prucnal, J.L. Stacy, and H.F. Bare, "Experimental demonstration of the simplest single-buffer deflection routing transparent optical node", OFC conference, CA, 1994

R. K. Boncek, P. R. Prucnal, A. Bononi, J. Sokoloff, J. L. Stacy, and H. F. Bare, "1.24416 Gbit/s demonstration of a transparent optical ATM packet switch node," Electron. Lett. 30, 1994

- Ultrafast signal processing, packet switching and communications systems demonstrations, including: ultrafast time-demultiplexing of bit-streams, ultrafast reading of packet-headers, self-routing control of photonic packet switches, an ultrafast fiber-optic network, two bits address recognition, and high-speed sampling of analog wave forms.

I. Glesk, P. R. Prucnal, and B. Wang, "Ultra-Fast Photonic Packet Switching with Optically Processed Control," OSA Spring Topical Meeting on Photonics in Switching, Salt Like City, Utah, March 12-17, 1995, accepted

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A. Bononi and P. R. Prucnal, "New structures of the optical node in transparent optical multihop networks using deflection routing," invited paper, submitted to J. High Speed Networks, special issue on Optical Networks.

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A. Bononi and P. R. Prucnal, "Analytical evaluation of improved transmission techniques in deflection routing networks," 28th Annual Conference on Information Science and Systems, session WP-1, Princeton, NJ, March 16-18, 1994.

A. Bononi and P. R. Prucnal, "New structures of the optical node in transparent optical multihop networks using deflection routing," in Proc. IEEE INFOCOM '94, Toronto, Ont., Canada, paper 3d4, June 1994.

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